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STRUCTURE AND EVOLUTION OF STARBURST AND NORMAL GALAXIES

Bahram Mobasher[1,2], Shardha Jogee[1], Tomas Dahlen[1], Duilia De Mello[3], Ray A. Lucas[1], Christopher J. Conselice[4], Norman A. Grogin[5], Mario Livio[1]

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ABSTRACT

A comparative study of the rest-frame morphology and structural properties of optically selected starburst galaxies at redshift $z \lesssim 1$ is carried out using multi-waveband ($BViz$) high resolution images taken by the Advanced Camera for Surveys (ACS) as part of the Great Observatories Origins Deep Survey (GOODS). We classify galaxies into starburst, early and late types by comparing their observed spectral energy distributions (SEDs) with local templates. We find that early-type systems have significantly higher rest-frame B-band concentration indices and AGN fraction (>25 %) than late-type spirals and optically-selected starbursts. These results are consistent with the scenario that early-epoch ($z \gg 1$) gas-rich dissipative processes (e.g., major mergers) have played an important role in developing large central concentrations in early-type E/Sa galaxies and that a concurrent growth of central black holes and bulges occur in some of these early merger events. The lower AGN fraction and concentration indices in the majority of the optically-selected starbursts at $z \lesssim 1$ suggest that either the starbursts and early types are different in nature (being respectively disk and bulge dominated), or/and are in different evolutionary phases such that some of the starbursts in major mergers evolve into early-types as the dynamical phase of the merger evolves and the spectral signature of the starburst fades out. The starbursts have, on average, larger asymmetries than our control sample of normal galaxies in both rest-frame B and R-bands, suggesting that a significant fraction of the starburst activity is tidally triggered.

Subject headings: galaxies: evolution — galaxies: starburst: galaxies

1. INTRODUCTION

A coherent picture of the formation and evolution of galaxies can only emerge through an understanding of starbursts over a wide range of cosmic lookback time. Starbursts drive galactic superwinds (e.g., Lehnert & Heckman 1996) which play a key role in the metal enrichment of the intergalactic medium and the establishment of the strong mass-metallicity relation in ellipticals and bulges (Lynden-Bell 1992). Moreover, the evolution of starbursts and active galactic nuclei (AGN) may be intimately linked through a common central gas supply and evolutionary effects (e.g., Norman & Scoville 1988; Kauffmann & Haehnelt 2000).

To date, detailed studies of star-formation have primarily targeted galaxies at high redshifts ($z \sim 2.5-5$) using optical (e.g., Steidel et al. 1999) and submillimeter (e.g., Hughes et al. 1998; Barger et al. 2001) emission. Conversely, in the local Universe ($z < 1$), studies of starbursts have mainly focused on dusty ultra-luminous infrared galaxies (ULIRGs) which show signs of strong interaction or double nuclei (Joseph & Wright 1985; Armus, Heckman & Miley 1987; Scoville et al 2000) and large gas densities (Sanders, Scoville, Soifer 1991). These are likely counterparts of high redshift sub-mm sources (Chapman et al 2003).

This paper focuses on a population of starburst galaxies which is different from those studied before. The sample of starbursts studied here is optically selected, complete to $R_{AB} = 24$ mag, and extends to $z \sim 1$. Therefore, the sample preferentially consists of relatively dust-free blue starbursts which differ in nature or in evolutionary stage from those selected at infrared wavelengths. Using multi-waveband high resolution images from the Advanced Camera for Surveys (ACS), obtained as a part of the Great Observatories Origins Deep Survey (GOODS), we compare the optically-selected starbursts at $z \lesssim 1$ to a control sample consisting of normal late and early type systems, and discuss their role in the evolution of these galaxies.

2. OBSERVATIONS AND SAMPLE SELECTION

2.1. *Observations*

The GOODS project consists primarily of space-borne (*HST*/ACS) and ground-based multi-waveband imaging of two fields, the HDF-N and CDF-S. In this study we consider only the Southern GOODS field (CDF-S) where most of the initial data have been obtained and processed.

The GOODS-ACS observations are performed in four bands ($BViz$), covering an area of $10' \times 16'$. The ground-based imaging observations cover the entire CDF-S area in $U'UBVRIJHK$ to the depths of $R_{\rm AB}$=25 mag and $K_{s_{\rm AB}}$=23 mag. A more detailed discussion of the GOODS observations is given in Giavalisco et al (2003).

2.2. *Photometric Redshifts and Spectral types*

The ground-based CDF-S data provide photometry in 14 passbands consisting of WFI ($U'UBVRI$), FORS (RI),

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218, USA; b.mobasher@stsci.edu
[2] Also affiliated to the Space Sciences Department of the European Space Agency
[3] Goddard Space Flight Center, Greenbelt MD 20771
[4] California Institute of Technology, Mail Code 105-24, Pasadena, CA 91125
[5] Physics and Astronomy Department, Johns Hopkins University, Baltimore, MD 21218

SOFI, and ISAAC (JHK). The observations cover the entire field except for the FORS and ISAAC observations which are deeper and only cover a sub-area of the field. Magnitudes measured over an aperture with a $3''$ diameter were used to construct the observed SEDs for all galaxies in the R-band selected survey. Photometric redshifts and spectral types were estimated for individual galaxies by fitting the observed and template SEDs using the Bayesian photometric redshift technique (Benitez 2000). The template SEDs consist of E, Sbc, Scd, and Im (Coleman, Wu & Weedman 1980), and starburst (Kinney et al 1996). A subsample of galaxies in the CDF-S have spectroscopic redshifts from the K20 survey (Cimatti et al 2002). Comparison between the estimated photometric and spectroscopic redshifts for these galaxies gives $\frac{z_{phot}-z_{spec}}{(1+z_{spec})} \sim 0.10$, which is taken as the error in photometric redshifts here. Additionally, the derived spectral types of the galaxies were found to be consistent with visually classified elliptical and spiral galaxies on the ACS images. A detailed study of the photometric redshift measurements for the GOODS field will be presented in Mobasher et al (2003).

2.3. *Sample Selection*

The starburst sample in this paper includes galaxies from the R-band selected ground-based survey which satisfy the following criteria: (a) They have starburst spectral types and $R_{\rm AB} < 24$ mag. The magnitude limit ensures that photometric redshifts and spectral types are measured more accurately ($\frac{\Delta(z)}{(1+z_{spec})} < 0.1$). (b) They have redshifts in the range $0.2 < z < 1.3$. Lower redshifts are excluded to minimize relative uncertainties in photometric redshifts and resolution dependent effects (see § 3). (c) They lie in the CDF-S area covered by the ACS. A control sample was also constructed (to the same magnitude limit) consisting of normal galaxies (i.e. non-starbursts), with early (E/Sa) and late (Sb–Sd) spectral types. Im galaxies are not included.

Given the selection criteria, our sample of starburst galaxies is biased towards relatively dust-free blue starbursts and against dusty star-forming galaxies. This study thus complements previous investigations of dusty starbursts and ULIRGs which were selected based on their infrared properties (e.g., Scoville et al 2000). It is to be noted that the SED fitting method used here does not fully guarantee that the selected objects are indeed starbursts. For example, a very metal poor galaxy with only modest amount of star formation could have a very blue color and hence, be classified as a starburst here. However, the number of such galaxies is expected to be small with the sample mostly dominated by galaxies experiencing bursts of star formation.

Table 1 presents the number of starburst and control galaxies in their observed frames, so that in the redshift intervals indicated, they correspond to the rest-frame B-band. The median absolute magnitudes for the three different types of galaxies in the present sample ($R_{\rm AB} < 24$) are $M_B = -19.6$ (starburst), -19.9 (Sb–Sd) and -20.6 (E/Sa). The median $U-V$ ($V-K$) colors for the starburst, late and early-type galaxies here are respectively estimated as -0.70 (1.80), -0.20 (2.40) and 0.35 (2.8). In order to check the sensitivity of our results to the adopted magnitude limit, the analysis in this letter (§ 3) was repeated to $R_{\rm AB} < 25$ mag, with no difference found.

3. STRUCTURE AND MORPHOLOGY

We quantify the concentration and asymmetry of the sample galaxies using the CAS concentration (C) (Bershady et al. 2000) and asymmetry (A) indices (Conselice et al. 2000). The concentration index is proportional to the logarithm of the ratio of the 80 % to 20 % curve of growth radii

$$C = 5 \times log(r_{80\%}/r_{20\%}). \quad (1)$$

The asymmetry index is obtained by rotating a galaxy image by π, subtracting it from its pre-rotated image, summing the intensities of the absolute value residuals, and normalizing the sum to the original galaxy flux. The concentration and asymmetry parameters are measured for the starburst sample in the rest-frame B-band ($C_{\rm B}$, $A_{\rm B}$) to $z \sim 1$, using different observed ACS bands in the appropriate redshift ranges, as shown in Table 1. Corresponding quantities were also derived in the rest-frame R-band ($C_{\rm R}$, $A_{\rm R}$). The rest-frame B and R bands are respectively sensitive to young stars and the underlying older stellar population.

In order to minimize resolution dependent effects and relative uncertainties in photometric redshifts, we constrain the redshift range to $z \sim 0.2$–1.3, where the change in spatial resolution ($0.05''$) is only a factor ~ 2, ranging from 160 pc to 400 pc, assuming a flat cosmology with $\Omega_M = 1 - \Omega_\Lambda = 0.3$ and a Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}. The structural comparisons in § 3.1–3.2 probe galaxy evolution over a time period where the age of the Universe varied from 6 to 11 Gyr. It is important to note that the starburst and control samples are defined purely based on SED fits to multi-band ground-based images, without using any morphological information. Thus, the derived structural parameters provide additional *independent probes* of the nature and evolutionary stages of these systems.

3.1. *Concentration and AGN fraction*

Figure 1 shows the distribution of rest-frame B concentration indices ($C_{\rm B}$) for the starburst galaxies and the control sample, divided into two redshift bins. The distribution of $C_{\rm B}$ in early-type systems is significantly skewed towards higher values compared to starburst galaxies. Results from both the T-test and the Kolmogorov-Smirnov test, listed in Table 2, confirm that the distribution of concentration indices for starburst and early-type galaxies are statistically different, both in the mean and the overall distribution. About 72 % of the early-type galaxies have $C_{\rm B} > 3.0$ compared to 12 % of the starburst and 18 % of the late-type galaxies (Table 2).

The data suggest that by $z \sim 1$, early-type systems have already developed large central light concentrations, which demarcate them from optically selected starbursts and late-type galaxies (Figs. 1a and 1b). These large concentrations are likely associated with bulges and spheroidal components. This was demonstrated by simulation of galaxies with de Vaucouleurs ($r^{1/4}$) law, which were found to have large $C_{\rm B}$ (> 3.4) values (Jogee et al. 2003, in prep.). Furthermore, comparison of our samples with the

CDF-S X-ray catalog (Alexander et al 2003) shows that a much larger fraction (> 25 %) of the early-type systems host AGNs compared to only 2% of the starbursts[6]. The larger AGN fraction and high $C_{\rm B}$ we find in early-types are in qualitative agreement with the high concentrations in AGN hosts reported by other studies (e.g., Grogin at al. 2003). One general scenario consistent with our results is that the early-type systems with large $C_{\rm B}$ developed their central structures (bulges and spheroids) in much earlier ($z \gg 1$) violent gas-rich dissipative episodes such as major mergers (e.g., Naab & Burkert 2001). A concurrent growth of bulges/spheroids and massive black holes may occur in some of these mergers (Kauffmann & Haehnelt 2000), consistent with the large AGN fraction in the early types.

What is the nature of the optically selected starbursts at $z \lesssim 1$ and what will they evolve into? Most of these galaxies have concentrations in the range $C_{\rm B}$=3.3–4.5, which are well below those shown by the majority (> 50 %) of early-type galaxies, but comparable to those of late-type spirals in the same redshift range. Low values in $C_{\rm B}$ can result from disk-like systems as revealed by fits to artificial galaxies with exponential disks (Jogee et al. 2003, in prep.). However, $C_{\rm B}$ in starbursts is more strongly influenced by very young stars than in early-type systems so that low $C_{\rm B}$ may also result from localized, off-centered star-forming regions which often exist in early stages of tidal interactions or mergers. Visual inspection of the starbursts confirms that they include disk-like systems as well as a large number of morphologically disturbed objects which show tails, double nuclei, and nearby companions with a range of luminosity ratios (1:10 to 1:1). In summary, the lower $C_{\rm B}$ and AGN fraction in the majority of optically-selected starbursts, compared to early-type systems, suggest two possibilities. Either the starbursts and early types are entirely different in nature (being respectively disk and bulge dominated), or/and are in different evolutionary phases (that some of the starbursts in major mergers evolve into early-types as violent relaxation sets in and starburst spectral signature fades out).

3.2. *Asymmetry*

Figure 2a shows the distributions of rest-frame asymmetry ($A_{\rm B}$) indices in the rest-frame B-band for the starburst and control sample. A larger fraction (50 %) of the starburst galaxies have a high $A_{\rm B} >0.3$, compared to early-types (13 %) and late-types (27 %) (Table 2). It is likely that large values of $A_{\rm B}$ are driven by irregular patterns of star formation which may either be *externally* triggered in tidally interacting/merging systems or *spontaneously* triggered in isolated galaxies. Asymmetries induced by dust lanes, caused by high inclinations, are not significant as most objects in our sample are moderately inclined, based on their estimated ellipticities. Fig. 2b shows the corresponding rest-frame $A_{\rm R}$ index, derived out to $z \sim 0.58$ (Table 1). $A_{\rm R}$ is less sensitive than the rest-frame B-band to massive young stars. Thus, tidally induced features in mergers (e.g., Jogee, Kenney, & Smith 1999), can lead to large values of $A_{\rm R}$. The presence of both large $A_{\rm B}$ and $A_{\rm R}$ in a large fraction of the starbursts suggests that a significant part of their SF is tidally triggered. High asymmetry values have also been previously noted in a local sample of infrared luminous starburst galaxies (Conselice et al 2000). Visual inspection of our images confirms this claim as the majority of the systems with large $A_{\rm B}$ (>0.4) and $A_{\rm R}$ (>0.35) indeed appear to be optically disturbed or/and to have nearby companions.

4. SUMMARY

From a comparative study of optically-selected starburst galaxies out to $z \lesssim 1$ and a control sample of normal (early-type E/Sa and late-type) galaxies, we find:

(1) The early-type systems have rest-frame B concentration indices and AGN fraction (>25 %) which are significantly higher than those of late-type spirals and optically-selected starbursts at $z \lesssim 1$. The results are generally consistent with the idea that early-epoch ($z \gg 1$) gas-rich dissipative processes (e.g., major mergers) have likely played an important role in developing large central concentrations in early-type E/Sa galaxies. The larger AGN fraction qualitatively supports scenarios leading to a concurrent growth of central black holes and bulges in some early merger events.

(2) The lower $C_{\rm B}$ and AGN fraction in the majority of $z \lesssim 1$ optically-selected starbursts, compared to early-type systems, suggest that either the starbursts and early types are different in nature (being respectively disk and bulge dominated), or/and are in different evolutionary phases (such that some of the starbursts in major mergers evolve into early-types).

(3) The $z \lesssim 1$ optically-selected starbursts, on average, have larger asymmetry indices than normal galaxies, both in rest-frame B and R-band. This suggests that a significant fraction of the starbursts may be tidally triggered.

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[6] Assuming 1.5*arcsec* as the maximum distance between the ACS B-band coordinates and the X-ray identified sources (Koekemoer et al. 2003). Extending the search to 6.0″ increases the number of starbursts to 7%.

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Table 1
Number of starburst and non-starburst (control) galaxies from the ACS BViz images

Redshift range	Filter	Starbursts	Non-Starbursts All	Non-Starbursts Early	Non-Starbursts Late
		Rest-Frame B-band			
$0.24 < z < 0.56$	F606W	54	451	100	351
$0.61 < z < 0.93$	F775W	102	377	122	255
$0.94 < z < 1.31$	F850LP	1	149	21	128
		157	977	243	734
		Rest-Frame R-band			
$0.20 < z < 0.32$	F775W	6	164	25	139
$0.33 < z < 0.58$	F850LP	50	391	89	302
		56	555	114	441

Table 2
Comparison of Structural Parameters for Starbursts and Non-Starbursts.

	Starbursts	Non-Starbursts All	Non-Starbursts Early	Non-Starbursts Late
	Rest-Frame B-band			
Mean $C_{\rm B}$	2.53	2.82	3.25	2.65
Student T-test[1]		3e-9	6e-28	4e-4
K-S Test[2]		0.10	7e-7	0.53
$C_{\rm B} > 3.00$	12%	31%	72%	18%
Mean $A_{\rm B}$	0.33	0.26	0.23	0.27
Student T test[1]		9e-4	7e-11	3e-2
K-S Test[2]		1e-6	1e-10	3e-4
$A_{\rm B} > 0.30$	50%	23%	13%	27%
	Rest-Frame R-band			
Mean $C_{\rm R}$	2.59	2.81	3.26	2.72
Student T-test[1]		3e-9	6e-28	4e-4
K-S Test[2]		0.43	9e-5	0.77
$C_{\rm R} > 3.00$	8%	29%	71%	18%
Mean $A_{\rm R}$	0.31	0.24	0.22	0.24
Student T test[1]		8e-4	5e-4	3e-3
K-S Test[2]		0.24	5e-4	2e-2
$A_{\rm R} > 0.30$	37%	15%	15%	15%

Note. — (1) The significance S of the Student's T-test when comparing the starburst sample to each of the control populations in columns 2 3 and 4. A small value (e.g.,<0.05) of S indicates that the 2 populations have significantly different means; (2) As in (1) but showing the significance in Kolmogorov-Smirnov ($K-S$) test. This is the significance level for the null hypothesis that the two data sets are drawn from the same distribution;

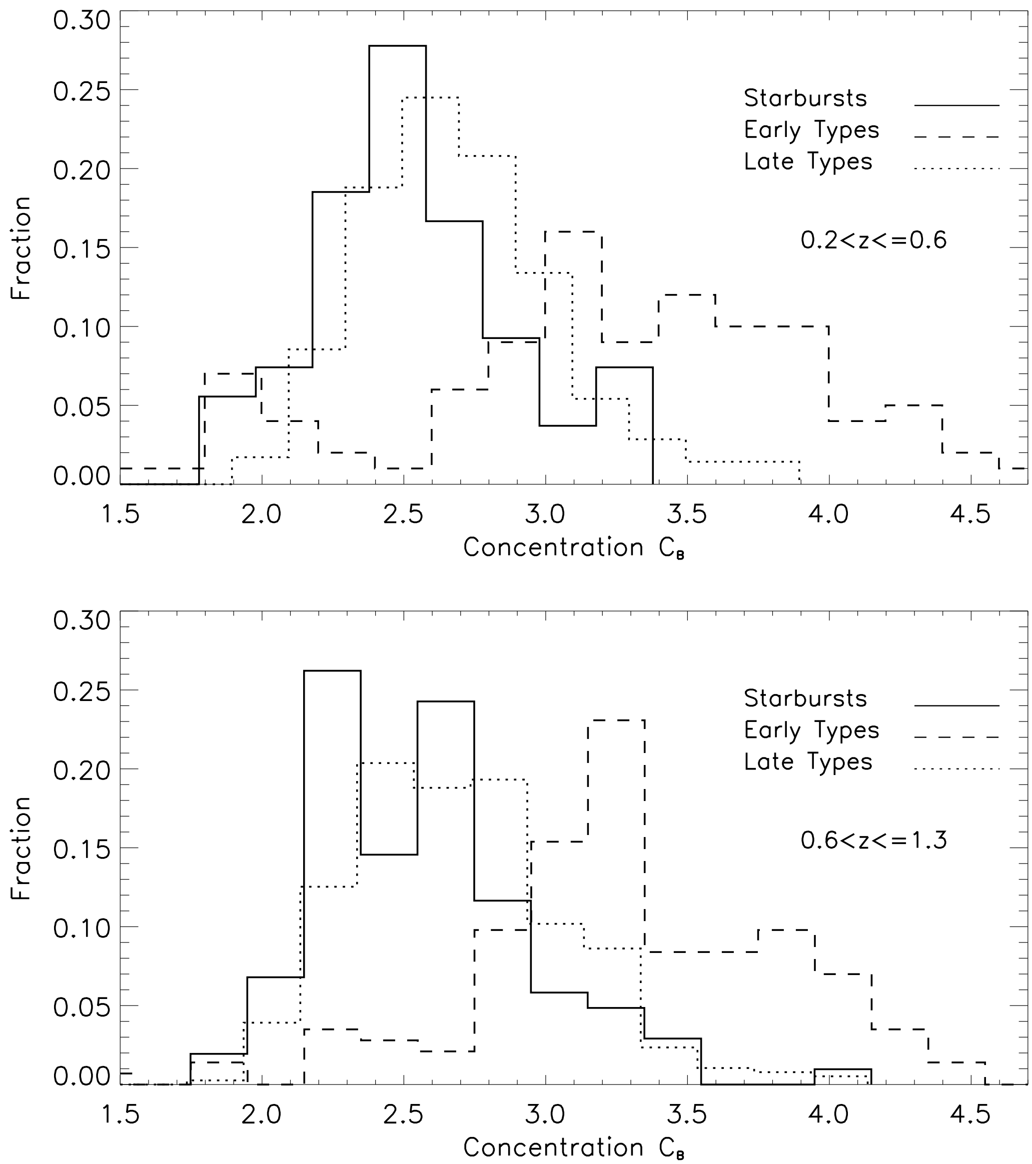

FIG. 1.— The distribution of concentration indices (C_B) in rest-frame B for the starburst, late, and early-type galaxies over two redshift intervals which are sampled as outlined in Table 1.

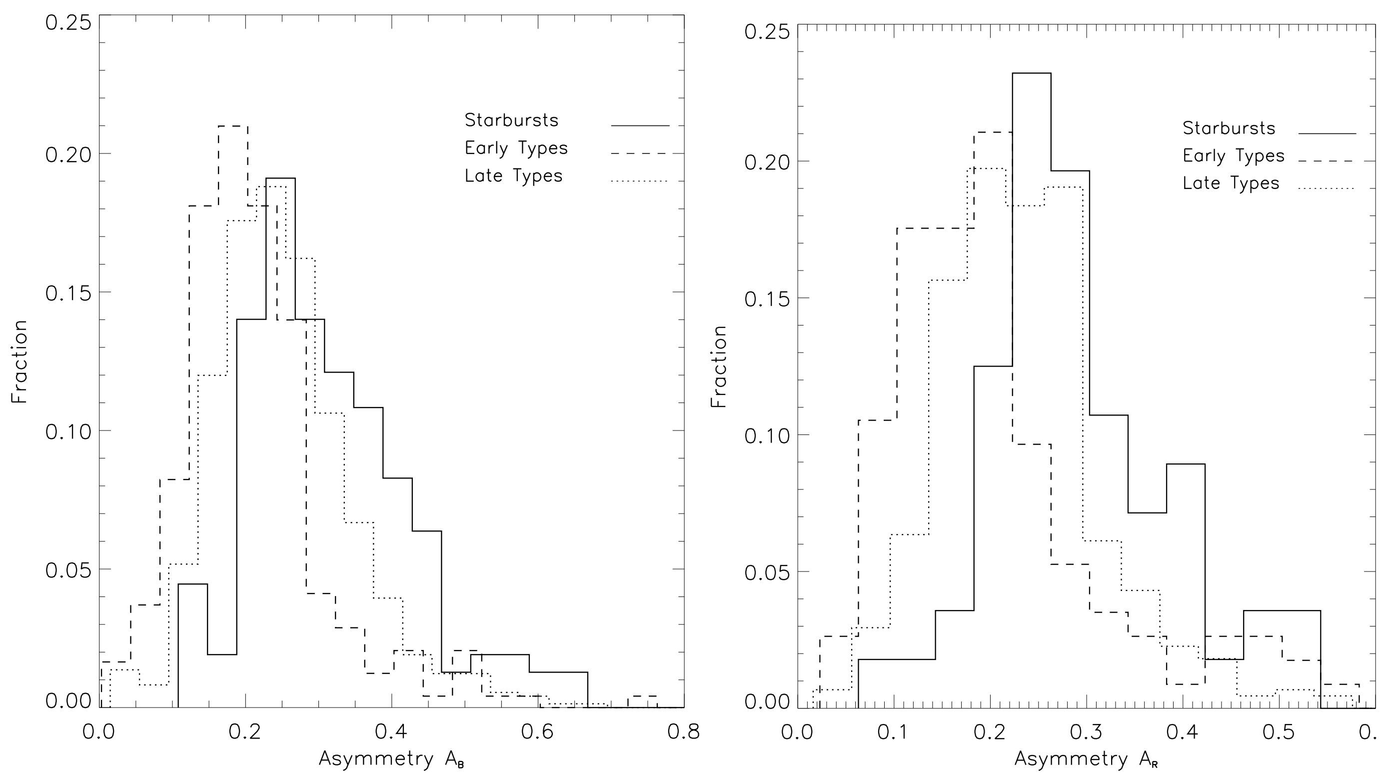

FIG. 2.— *Left: (a)* The distribution of asymmetry indices (A_B) in rest-frame B for the starburst and control sample. *Right: (b)* As in (a), but for the rest-frame R-band asymmetry indices. The redshift ranges covered (a) and (b) are listed in Table 1.